The importance of a small ephemeral tributary for fine sediment dynamics in a main-stem river

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Abstract

Studies of ephemeral streams have focused mainly in arid and semi-arid regions. Such streams also occur widely in temperate regions, but much less is known about their influence on fluvial processes in main-stem rivers here. In this paper we present evidence of the importance of a small ephemeral temperate stream for main-stem fine sediment dynamics. The paper focuses on a restoration project (River Ehen, NW England) which involved the reconnection of a headwater tributary to the main-stem river. We present data on suspended sediment transport two years prior to and two years following the reconnection. Despite the small size and non-perennial flow of the tributary, its reconnection resulted in an increase of 65% in the main-stem sediment yield. During both the pre- and post-reconnection periods, a higher proportion of the annual yield was conveyed during short events with relatively high suspended sediment concentrations. Following the reconnection, the magnitude and frequency of such events increased, primarily due to sediment being delivered from the tributary at times when main-stem flows were not elevated. Overall, the main-stem remains supply limited and so is highly dependent on sediment delivered from the tributary. The study helps stress that even non-perennial tributaries yielding only a small increase in catchment size (+1.2% in this case) can have a major influence on main-stem fluvial dynamics. Their role as sediment sources may be especially important where, as in the case of the Ehen, the main-stem is regulated and the system is otherwise starved of sediments.

Keywords: Ephemeral stream, fine sediment, suspended load, channel reconnection, river restoration, temperate region, regulated river, River Ehen.

1. INTRODUCTION

The transport dynamics of the finer fraction of river sediment loads (i.e. material finer than 2 mm diameter) have been studied intensively. Fine sediment generally represents the most important part of the sediment budget of a river (Walling and Webb, 1987; Vericat and Batalla, 2006) and so is quantitatively significant. Fine sediment is also important functionally, because of the role it plays in habitat formation. For example, fine particles play an important role as architects of riverbed structure, and help strengthen the banks, encourage the establishment of vegetation, enhance bed compactness and clog gravel interstices (Parker, 2003; Church, 2006). Fine sediment also has important implications for the entrainment of coarser bed material (Dudill *et al.*, 2016 and references therein) and may have negative effects on benthic organisms when present in excessive amounts (Wood and Armitage, 1997; Jones *et al.*, 2012). Interest in the effects of fine sediment on aquatic organisms was triggered primarily by concerns over human activities such as agriculture, deforestation and mining (Rabení *et al.*, 2005). However, some rivers carry naturally high fine sediment loads, whether as a result of glacial processes (e.g. Gurnell *et al.*, 1996) or loss of material highly erodible surfaces (e.g. badlands; Buendía *et al.*, 2011). Irrespective of whether causes are natural or anthropogenic, increased fine sediment loads generally lead to reductions in the diversity of aquatic organisms (Buendía *et al.*, 2013). Nonetheless, the exact response of organisms remains difficult to predict because effects depend on the interaction of factors such as concentration, duration of exposure, particle-size distribution and chemical composition (Bilotta and Brazier, 2008).

The variety of effects of fine sediment in rivers reflects differences in sediment sources and characteristics (Sear *et al.*, 2016), and the processes involved in its production, transport and deposition through the channel network (Wood and Armitage, 1997). Primary sediment production areas are confined largely to upper (i.e. headwater) parts of catchments (Charlton, 2008). Tributaries can have a major influence on the delivery of fine material to main-stem channels (Webb *et al.*, 2000; Collins and Walling, 2006), although this can vary over short temporal and small spatial scales, linked to hydro-climatic, hydrologic and hydraulic conditions (Buendía *et al.*, 2014; Piqué *et al.*, 2014). Some of this variability stems from spatial variation in the relative availability of fine sediment sources, and how local variation in precipitation interacts to switch different tributaries *on-and-off* at different times (López-Tarazón *et al.*, 2011; Tena and Batalla, 2013).

Interest in tributaries and their confluences has increased since the 1980s, with work focusing on the effects of tributary sediment delivery on downstream morphology (Rice and Church, 2001), sedimentary conditions (Rice and Church, 1998) and ecology (Rice *et al.*, 2001, 2008). Most emphasis has been on the role of relatively large, perennial tributaries in supplying coarse material to main-stem reaches (Benda *et al.*, 2004; Ferguson *et al.*, 2006), with a particular focus on downstream fining and the effects of tributary inputs on the fluvial equilibrium of the receiving river (Pizzuto, 1995; Rice, 1998). Less work has been conducted on fine sediment delivery from small, low-order tributaries, although exceptions include studies on the Colorado River, USA (Webb *et al.*, 2000; Griffiths and Topping, 2015) and the River Isábena, Spain (Francke *et al.*, 2014).

Historically, catchment-scale studies have relied on traditional mapping techniques (i.e. aerial photographs, satellite imagery and survey maps) to provide information on river channel characteristics that are relevant for helping to understand sediment fluxes (e.g. drainage density, length of channel network, slope). However, these techniques lack the resolution to characterise low-order streams (i.e. smaller headwater tributaries; Benstead and Leigh, 2012) and, consequently, the extent of such streams may be underestimated (Meyer and Wallace, 2001). For the most part this has not been seen as problematic, as the influence of small tributaries on main-stem river reaches has been considered inconsequential (sediment contribution thought to be simply a function of size; Rhoads, 1987; Benda *et al.*, 2004). This view is reinforced by the fact that many small tributaries are intermittent and so deliver material infrequently (Datry *et al.*, 2014). However, others have argued that the role of these small systems has been under-estimated (Benstead and Leigh, 2012). Tena *et al.* (2012) found that the sediment contribution from intermittent tributaries increased the maximum suspended sediment concentration of a main-stem river three-fold. However, like many studies of intermittent or ephemeral streams, this work was undertaken in a dryer region (the Mediterranean); studies of the importance of such streams in other regions (e.g. temperate ones) remain scarce.

In this paper we present evidence of the importance of small, ephemeral tributaries for fine sediment dynamics in main-stem rivers located in temperate regions. The paper is focused on a headwater tributary of the River Ehen in NW England. Flows in the main-stem Ehen are regulated by a lake and associated weir. A tributary (Ben Gill) that enters the Ehen just downstream from the weir was diverted in the 1970s as part of the water supply network, such that for more than 40 years it no longer delivered its sediment and water to the Ehen. However, it was reconnected in autumn 2014. We demonstrate the importance of this tributary by presenting data on the suspended sediment load of the Ehen two years before and two years after the reconnection. We also discuss the timing and magnitude of fine sediment loads in the

Ehen in relation to hydrological conditions. Specific objectives of the paper are to: (i) characterise variation in fine sediment transport across a variety of temporal scales (event, annual, and pre- vs. post-reconnection), (ii) assess contribution of the tributary to the fine sediment load of the Ehen, and (iii) assess the links between fine sediment dynamics and the flow regime.

2. STUDY AREA

The River Ehen flows south-westwards and discharges to the Irish Sea (Figure 1A & B). It has a total catchment area of 155.8 km^2. The hydrological regime of the Ehen is regulated by Ennerdale Water, although because of the water abstractions and the design and management of the weir, impacts are limited mainly to modification of low flow percentiles. The lake is an important drinking water supply for West Cumbria. It is a natural water body (occupying a formally glaciated valley), although its storage capacity was increased by the construction of a 1.3 m high weir (in 1902) and the diversion of Ben Gill (in the 1970s, Figure 1C). Ben Gill is a first order ephemeral headwater tributary, with a small (0.55 km^2), steep (mean catchment slope: 25%) mountainous and responsive catchment. It is considered to be ephemeral (as opposed to intermittent) as it flows for less time than it is dry, and usually in response to rainfall (Uys and O'Keeffe, 1997). When flow recedes, Ben Gill is left dry along most of its length. Although it is not gauged, previous estimates suggest that it flows for approximately ¼ of the time (Quinlan *et al.*, 2015a).

The upper section of Ben Gill flows over a series of waterfalls and step-pool sections, where it forms a steep gully. This upper section represents 85% of the total length of the Ben Gill and has always remained highly dynamic due to its steep gradient. Dominant vegetation here consists of shallow acid grassland with heather and bracken. When it reaches the valley floor, the channel flattens out. Consequently, prior to its diversion, sediment transported from the upper section of Ben Gill deposited to form an alluvial fan in the 300 m long lower section. Average gradient here is 9% and landcover is rough pasture. Originally, Ben Gill discharged to the Ehen approximately 40 m downstream from the lake outlet (i.e. weir). In the 1970s it was diverted into the lake through an underground culvert positioned at the marked break in slope between the upper and lower sections (Figure 1C). Thus, the relatively long upper section has remained a functional channel, while the short section (~15% of total length) below the diversion point, where it crosses the fan, was filled in and has terrestrialised. Since the diversion, sediment supplied from the upper section accumulated around the culvert, and was periodically removed and used locally as building material.

Discharge (hereafter *Q*) in the River Ehen is gauged at Bleach Green (Figure 1C). The catchment area here is 44.5 km^2. Although this is only 28% of the total catchment of the River Ehen, this upper area contributes 45% of the catchment's 1800 mm long term mean annual rainfall (Alvarez-Codesal and Sweeting, 2015). The river at Bleach Green has a long term mean daily *Q* of 2.70 $m^3 s^{-1}$ (1973-2016 data) with minimum and maximum daily *Q* of 0.124 and 80.2 $m^3 s^{-1}$ respectively. The compensation flow released from the weir (via a fish-pass) has varied over time; it was 0.37 $m^3 s^{-1}$ until 2012 but is currently 0.92 $m^3 s^{-1}$, sometimes phased down to 0.69 $m^3 s^{-1}$ depending on lake level.

Ennerdale Water acts as a sediment trap, with limited sediment transfer to the section immediately downstream (Quinlan *et al.*, 2015a). Further downstream, the river meanders through argillaceous rocks of the Skiddaw group and sandstones (Brown *et al.*, 2008). Here, important sediment contributions come from bank erosion, tributary inputs and diffuse agricultural runoff.

The Ehen was designated as a Special Area of Conservation (SAC) in 1995 as it supports an estimated 550,000 freshwater pearl mussels *Margaritifera margaritifera*, L. (Killeen and Moorkens, 2013), the largest remaining population in England. As part of work to help conserve this important population, Ben Gill was reconnected to the Ehen in October 2014, in an attempt to reactivate the delivery of coarse sediment. The diversion culvert was disabled and a new 300 m long section of channel was engineered over the alluvial fan, following the approximate course of the original stream. The bed of the new section was lined with cobble-size material, with some larger (boulder-size) clasts along the banks (see Marteau *et al.*, 2016 for more details). In an attempt to limit the first flush delivery of fine sediment to the main-stem, the bed was thoroughly washed, section-by-section, before the most downstream point was excavated and opened to connect to the Ehen. The wash-water was stored in temporary off-channel settlement ponds; settled fine material was removed from site, with remaining wash-water pumped to the lake.

Figure 1.

3. METHODS

3.1. Rainfall and discharge

The current study is focused on a 4-year period, covering the two hydrological years immediately before the reconnection of Ben Gill (i.e. October 2012 – September 2014) and the first two years after (i.e. October 2014- September 2016). Daily precipitation was recorded by the Environment Agency at Ennerdale Bridge, 1.8 km downstream from the Ehen-Ben Gill confluence. The River Ehen is gauged by the Environment Agency at Bleach Green (Figure 1C; see Quinlan *et al.*, (2015a) for more details). Discharge data from Bleach Green (15-min interval) were used to produce time-series for the study period. Additionally, mean daily values for the 1974-2016 period were used to compute flow percentiles and values of water yield, to set the study period within a longer-term perspective.

3.2. Suspended sediment

Turbidity (NTU) was measured in the Ehen at Bleach Green using a YSI® 6600 probe with self-cleaning wipers. The manufacturer reports a 0.1 NTU resolution for this instrument, with an accuracy of ±2% or 0.3 NTU (whichever is greater). Turbidity was recorded at 15-min intervals over the 4-year study period. The probe was maintained by the Environment Agency, and retrieved for cleaning and calibration every 2 to 3 months. Quinlan *et al.* (2015a) generated an NTU-Suspended Sediment Concentration (SSC) calibration prior to the reconnection of Ben Gill. This calibration was produced by sequentially adding fine sediment (collected from the bed at Bleach Green) to a bucket of water to create known concentrations, with turbidity measured for each increment in sediment (further details in Quinlan *et al.*, 2015a). The present study uses the pre-reconnection data produced by these authors, except that for the calibration curve the regression was forced through the origin. This calibration is used to derive SSC values and compute sediment loads for the pre-reconnection period. Because of the very low values of turbidity recorded by Quinlan *et al.* (2015a) (a maximum of 8.6 NTU), this calibration only encompassed the lower end of the probe's range (0-400 NTU). A second calibration was produced for the post-reconnection period, using the same procedure but covering the entire range of the probe (0-1000 NTU) to capture the greater turbidity values recorded post-reconnection; this was used to estimate SSC and loads for this period. The difference in range covered by the two calibrations does not impact interpretation of the results since each curve is used only to compute SSC and load within its own range (i.e. the ranges recorded within respective periods).

The slope of the NTU-SSC relationship prior to the reconnection was 2.06 (regression r^2 = 0.99, P < 0.001; Figure 2) while that for the post-reconnection period was 1.66 (r^2 = 0.99, P < 0.001). These slope values are significantly different (Ancova, df = 81, F = 229.19, P < 0.001).

Organic content of fine sediment remained low (below 10% on average), with no apparent seasonal or annual variations. The highest values of organic content were measured at very low SSC, and could not be differentiated from uncertainties associated with the probe accuracy and laboratory processing procedures. Thus, no attempt was made to correct SSC values for organic content.

Suspended sediment load (SSL) and water yield were computed from 15-min data. SSL was calculated by multiplying SSC by Q for 15-min time steps. Values were then summed to compute loads at the monthly and annual timescales.

Figure 2.

4. RESULTS

4.1. Hydrological context

Over the 4-year study period, precipitation averaged just under 2000 mm per year. Annual precipitation values were 1799 mm in 2012-2013, 1901 mm in 2013-2014, 1921 mm in 2014-2015 and 2329 mm in 2015-2016. Most events were less than 20 mm per day, with a total of 9 events exceeding 50 mm (Figure 3A). An exceptional rainfall event, the highest recorded during the 4 years, occurred on the first day of the reconnection: in total, 104 mm fell within the 24 hour period, with impacts on the morphology of the new channel (Marteau *et al.*, 2016) and implications for fine sediment delivery to the main-stem (detailed in Section 4.2). The 2014-2015 hydrological year was the wettest within the study period, with precipitation 26% greater than the two pre-reconnection years.

Despite being regulated by Ennerdale Water and its weir, the Ehen remains relatively flashy and regularly experiences high flows (Figure 3A). Its flow regime follows typical patterns for the NW of England, with lower flows in late spring and summer and higher flows in the winter, but with some high events also occurring in late summer. The median discharge (Q_{50}, the discharge exceeded for 50% of the time) for the study period was 1.98 $m^3 s^{-1}$, which is greater than the long-term median value (1974-2016 = 1.38 $m^3 s^{-1}$). Minimum mean daily Q was 0.71 $m^3 s^{-1}$ (30/07/2013) while minimum instantaneous Q was 0.31 $m^3 s^{-1}$ (11/02/2015). Maximum mean daily Q was 44.5 $m^3 s^{-1}$ (15/11/2015, $Q_{0.02}$), with the instantaneous maximum value being 54.0 $m^3 s^{-1}$. This maximum has only been exceeded twice over the 42-year period of record (CEH, National Flow Archive website, AMAX dataset).

Figure 3.

Flow duration curves (Figure 4) indicate that the 2015-2016 hydrological year was substantially wetter than the 3 previous years, with higher median, mean and maximum Qs. Low flows were similar for each year of the study period, with most of the differences observed at higher flows (approximately Q_{10} and higher); for example, Q in 2015-2016 was above 10 m^3 s^{-1} for almost 10% of the time, markedly higher than the 3 other years (between 4 and 5% of the time). The flow duration curve for year immediately preceding reconnection (2013-2014) was very similar to the years before and after, differing only for the highest range of discharges, which were exceeded only around 0.2% of the time. The occurrence of both similar and rather different hydrological regimes pre- and post-reconnection provides a useful basis for assessing the effects of the reconnection on suspended sediment transport.

Figure 4.

4.2. Variations in suspended sediment transport

Episodes of high SSC were generally scarce during the pre-reconnection period (Figure 3B). The two most important periods of fine sediment transport were in summer 2013. These occurred during floods that followed a prolonged period of low flow; they peaked at 190 mg l^{-1} but were short-lived (max 24 hours). The high rainfall event on the first day of the reconnection generated visible erosion in the newly created Ben Gill channel, and was responsible for a plume of fine sediment entering the main-stem of the River Ehen. Turbidity exceeded the probe's maximum value (1000 NTU) for 15 minutes during the day, and so the calculated SSC of 1700 mg l^{-1} is probably an underestimate of the true instantaneous value. This value represents a nine-fold increase in maximum instantaneous SSC compared to the maximum recorded pre-reconnection. Although such an extreme value has not been recorded again (as of September 2016), high SSC values have proven to be more frequent after the reconnection of Ben Gill; for instance, the maximum pre-reconnection SSC of 190 mg l^{-1} has been exceeded seven times since October 2014, including some long-lasting events (Figure 3B).

The relationship between Q and SSC has been affected by the reconnection, as indicated by the difference between Figure 5 A and B. The relationship prior to the reconnection shows little scatter, with the majority of the highest SSC events confined to low discharges (Figure 5A). The difference post-reconnection is most evident at low and medium discharges (Figure 5B). While patterns remain unchanged at high flows (green square, Figure 5B), the scatter in the relationship is considerably greater below 20 m^3 s^{-1}; this is particularly visible for flows below 5 m^3 s^{-1} (blue square, Figure 5B). Overall, Figure 5 illustrates how the magnitude of SSCs increased following the reconnection, and how the reconnection has altered the basic hydraulic and sedimentary dynamics of the Ehen.

Figure 5.

Despite the increased frequency and magnitude of high SSC events following the reconnection, it is notable that there is no marked difference in the respective mean and median values (Table 1). Note also that maximum SSCs in 2015-2016 coincided with very high flows ($Q_{0.02}$) which lead to appreciable volumes of sediment being transported through the channel (between 57 and 60 t per month, in November and December 2015; Figure 6).

Table 1.

4.3. Contribution of the tributary to main-stem sediment loads

Water yield followed a similar pattern each year (Figure 6), with low values in early summer (June) and high values in early to mid-winter (November to January). Maximum (26.84 hm^3) and minimum (2.45 hm^3) monthly water yields were recorded in December 2015 and June 2014 respectively. Prior to the reconnection, monthly suspended sediment load (SSL) tended to follow the same pattern as water yield, with greater volumes of water leading to higher sediment loads. In the month that the reconnection took place (October 2014), SSL was the highest recorded during the study period (65.4 t); notably, this high value followed on the back of the lowest SSL value recorded (September 2014, 1.81 t). Patterns of monthly SSL in 2015-2016 were more difficult to explain solely by water yield. For instance, floods in November and December triggered monthly SSLs similar to October 2014, but water yields were appreciably higher (around 25 hm^3 in November and December 2015 compared to only 13 hm^3 in October 2014). Additionally, similar amounts of sediment were transported in January 2014 and August 2016, although water yields were different between these months.

Figure 6.

Annual water yield was generally similar for the first three years of the study (ranging between 93 and 105 hm^3), but increased markedly in the final year (132 hm^3; Figure 7A). Overall, these values sit slightly above the long-term average of 85.4 hm^3 (1974-2016 data). Sediment yield was similar for the two pre-reconnection years (153.1 and 149.6 t, Figure 7A) but post-reconnection values increased by 65% on average (i.e. 250.9 and 251.2 t, Figure 7B), highlighting the role of Ben Gill in supplying sediment. Post-reconnection, water yields were also slightly higher (7% in 2014-2015, and 36% in 2015-2016), reflecting the higher precipitation values (+4% and +26% respectively).

Figure 7.

4.4. Links between fine sediment dynamics and flow regime

The cumulative frequency curves (Figure 8) provide an insight in the transport duration of both water and sediment yields. Despite sitting on either side of the reconnection, transport durations of the water yield for the years 2012-2013 and 2014-2015 were similar, as were the years 2013-2014 and 2015-2016. Overall, 50% of the water yield was transported within 20% (2012-2013 and 2014-2015) to 25% (2013-2014 and 2015-2016) of the time. The similarity suggests that the reconnection of Ben Gill did not create a shift in time concentration patterns for water yields. However, time-concentration for the sediment loads clearly shifted after the reconnection, with a higher proportion of sediment transported in a much shorter amount of time in the post-reconnection period. For instance, 1% of the time concentrated 17 to 23% more of the sediment yield after the reconnection. This was true for both of the post-reconnection years, regardless of differences in their hydrology and the magnitude of the sediment yield. The higher proportion of sediment now being transported in a shorter amount of time reflects the increased importance of intense but short-lived SSC events (Figure 3B).

Figure 8.

5. DISCUSSION

5.1. Context

Non-perennial water courses compose a substantial proportion of the total length, number and discharge of the world's streams and rivers (Datry *et al.*, 2014). They are diverse (hydraulically, geomorphologically and ecologically) and widespread, being found in most terrestrial biomes (Larned *et al.*, 2010). Temperate regions support many non-perennial streams which, just like their dryland counterparts, are experiencing altered hydrological regimes related to global change (Stanley *et al.*, 1997). Studies designed to understand their importance for sediment supply are crucial to assess the likely impacts of future changes in climate, land cover or water use on river integrity. Ben Gill is an example of a non-perennial stream in a temperate region; it is notable in being ephemeral despite being located in the wettest region (the NW) of England.

Though not grossly different, there were a number of differences in the flow regimes of the study years, with corresponding differences in water yield. Most of the variability related to the major floods of winter 2015; these resulted in higher water yields but had no impact on the time concentration of transport (Figure 8). Moreover, the higher water yield in 2015-2016 was found to be a simple response to increase in precipitation (+26% compared to pre-reconnection period) rather than any potential effect of the reconnection. Although we did not measure turbidity or SSC within Ben Gill itself, no changes other than the reconnection occurred in the upper part of the catchment over the study period; thus, we attribute this major change in fine sediment yield to a small (0.55 km^2), headwater tributary which only flows for approximately ¼ of the time.

5.2. Sedimentary effects of the reconnection in the Ehen

Temporal variation in fine sediment transport

Ben Gill has experienced much erosion since it was reconnected, and this has resulted in the delivery of both fine and coarse sediment to the Ehen. Marteau *et al.* (2016) estimated that a minimum of 150 m^3 of sediment was delivered to the Ehen in the first six months after the reconnection. Data presented in the current paper indicate that large volumes of fine material are also now being delivered as a result of the reconnection.

The very high SSC recorded on the day following the reconnection coincided with an unusually high local rainfall event. This coincidence of timing was unfortunate from a management perspective, given the sensitivity of aquatic organisms to fine sediment. Despite efforts by the engineering company to remove fine particles from the newly created channel immediately prior to the day of the reconnection, it is possible that a small part of the plume of sediment was linked to the flushing of fine material remaining on the bed surface. Over 35.7 t of fine entered the Ehen from Ben Gill over 48h, representing 55% of the month's sediment yield and approximately 14% of the annual yield. We conclude that, given the scale of the rainfall event and the magnitude of the erosion it generated, most of the plume originated from the erosion of subsurface fine material.

Maximum SSC values in the Ehen have increased post-reconnection, but this is not the case for minimum and mean values, and the quartiles. This difference indicates that fluvial dynamics in the Ehen at base-flow remain largely unaffected by the reconnection. Moreover, the time concentration of suspended sediment yield has changed since the reconnection, with a higher proportion of the sediment yield now being transported through the channel in a shorter period of time. This supports the conclusion that the influence of Ben Gill on annual fine sediment yields comes through large volumes of material being transported during short-lived events, when Ben Gill is flowing.

Contribution of Ben Gill to the River Ehen fine sediment yield

Suspended sediment loads in the Ehen following the reconnection increased by 65% on average. This major change is evident despite the fact that Ben Gill increased catchment size at the confluence by only 1.2%. The increased load equates to an increase in specific sediment yield from 3.39 t km^2 $year^{-1}$ pre-reconnection to 5.56 t km^2 $year^{-1}$ post-reconnection. If we consider the average increase of 100 t y^{-1} to be eroded from Ben Gill catchment, then the specific yield from this tributary can be estimated at around 181 t km^{-2} $year^{-1}$.

Specific yields for the Ehen catchment are rather low when compared to other catchments, while those for Ben Gill are closer to the higher values reported in the literature. For example, Worrall *et al.* (2013) reported a long-term average sediment flux of 22.2 t km^{-2} y^{-1} for the UK (5^{th} percentile and 95^{th} percentile of 5.4 and 107.7 t km^{-2} $year^{-1}$ respectively). Foster and Lees (1999) reported long-term sediment yields of 7 to 86 t km^{-2} $year^{-1}$ from their own research in the North of England, set against published values for the region ranging from 0.8 to 488 t km^{-2} $year^{-1}$ (see references therein). They argue that the higher values can be attributed to human alterations to catchments, including agriculture and heather burning (Foster and Lees, 1999). The estimated specific sediment yield of over 180 t km^{-2} $year^{-1}$ for Ben Gill falls close to the range of yields recorded in ephemeral Mediterranean basins (50 to 200 t km^{-2} $year^{-1}$, Walling and Webb, 1996; Rovira and Batalla, 2006). This highlights the potential for small ephemeral tributaries to deliver large volumes of sediment regardless of their size and hydrology.

Links between fine sediment dynamics and flow regime

In general, flows in the Ehen and Ben Gill are rather synchronous (Quinlan *et al.*, 2015a). However, they are occasionally out of phase and maximum SSCs in the Ehen occur during the rare times when Ben Gill is flowing but flows in the Ehen are not elevated much beyond base-flow. When sediment delivered from Ben Gill coincides with high Q in the Ehen, it is diluted and quickly conveyed downstream; exhaustion occurs once Ben Gill again ceases to flow, which is typically rather soon. Thus, hydraulically speaking the Ehen could carry more sediment, but remains limited by the supply during floods; i.e. it will transport sediment as long as material is available. This and the ongoing adjustment in sediment dynamics after the reconnection are reflected in the Q-SSC relation observed in the Ehen, which contains much scatter; less than 0.01% of the variation in SSC can be explained by variation in Q (Figure 5). Fluvial dynamics at low flows are largely controlled by the timing of sediment supply from Ben Gill, with potentially very high SSC events occurring (blue square, Figure 5B). Material from previous high SSC events temporarily stored in the bed of the Ehen becomes available for transport on the rising limb of hydrographs, but is quickly exhausted. The scatter shows the variability in the amount of sediment available in the channel (red square), which remains very limited. Subsequent higher *Q* have no influence on SSCs, because all the material has already been exhausted, or inputs from Ben Gill are diluted by the large volumes of water (green square, Figure 5B). Thus, the influence that the reconnection is having on the *Q*-SSC relationship in the Ehen remains limited to low-intermediate discharges. This indicates that despite its small contributing area, Ben Gill is affecting the basic hydraulic-sediment transport relations in the Ehen for a certain range of *Qs*.

5.3. Implications

Potential ecological consequences for the River Ehen

The reconnection of Ben Gill forms part of catchment-wide initiative in the Ehen focused on conservation of freshwater mussels. The reconnection aimed to help re-naturalise the hydrological regime of the Ehen and supply the coarser sediment which is an important part of the habitat required by mussels. New coarse sediment is now delivered to the Ehen (Marteau *et al.*, 2016), so one of the objectives of the reconnection is already being achieved. However, it is also clear that Ben Gill is now delivering much fine sediment; indeed, data indicate that it has become the main driver of suspended sediment dynamics in the section of the Ehen immediately downstream from the confluence. This has potential implications for biota, not just because of the absolute volumes involved but because temporal mismatch between sediment released from Ben Gill and high flows in the Ehen can lead to high SSC events at relatively low discharges, facilitating in-channel sedimentation. The effects of this sedimentation on biota can be direct (abrasion, clogging of gills) and indirect (deposition and subsequent consequences for benthic habitat), causing, for instance, changes in macroinvertebrate drift patterns (Béjar *et al.*, 2017), and reduced survival of salmonid embryos (Sear *et al.*, 2016) and freshwater pearl mussels (reviewed by Quinlan *et al.*, 2015b).

Effects of the reconnection on fine sediment in the Ehen are not limited to changes in concentration and load. The empirical calibration produced for the post-reconnection period yielded a regression coefficient which was significantly different to that for the pre-reconnection period (Figure 2). This shift in the NTU-SSC relationship can be interpreted as a change in the quality of suspended sediment; material found in suspension now differs in composition (particle size, shape, colour, organic content etc.) compared to before the reconnection. This change may be critical ecologically (see for example Sear *et al.* (2016) in relation to fish, and Österling *et al.* (2010) in relation to pearl mussels). Thus, understanding how this new source of fine sediment is affecting in-channel fine sediment patterns, both quantitatively and qualitatively, as well as its effects on biota, will be key for assessing the overall effects of the reconnection.

Wider repercussions

Climate models suggest that the number of non-perennial streams will increase globally in the near future, particularly in regions where water appropriation is occurring (Larned *et al.*, 2010). While arid and semi-arid regions will see patterns of intermittency shift towards a reduction in the number of days of flow (e.g. Garcia *et al.*, 2016), temperate regions are predicted to experience increased seasonality in flows, with increased high flow magnitudes and reduced low flows (van Vliet *et al.*, 2013). In some areas, the latter may result in small perennial streams becoming intermittent or even ephemeral. The significant influence of Ben Gill on sediment dynamics in the Ehen helps stress the functional implications of tributaries becoming disconnected from their main-stems due to changes in flow.

Globally, the erosion and fluxes of fine sediment have been altered dramatically by human activities. Land clearance, mining and agriculture are important causes of larger volumes of soil and fine sediment now being washed into river networks (Trimble and Crosson, 2000; Walling, 2006), while dams trap a substantial fraction of fine material and so reduce loads (e.g. 60%, Yellow River, Walling, 2006; around 90%, River Ebro, Vericat and Batalla, 2006). Our study of the Ehen indicates that the disconnection of headwater tributaries may have a major influence on fine sediment fluxes (e.g. Zhang *et al.*, 2015). However, it also shows that reconnection of such tributaries can help restore hydro-sedimentary dynamics, and that the reconnection of even small watercourses can play an important role in river rehabilitation efforts.

6. FINAL REMARKS

The Ehen system is regulated and, as a whole, remains supply limited (as per Quinlan *et al.*, 2015a) and highly dependent on sediment delivered from Ben Gill. Our results indicate that the transport of fine sediment in the Ehen is not hydraulically driven (i.e. not controlled solely by increases in discharge) but relies greatly on the ephemeral characteristics of Ben Gill. Despite its limited influence on the hydrology of the Ehen, Ben Gill’s impacts include quantitative and qualitative aspects of the fine sediment flux, as well as the temporal dynamics of this flux. The work shows that small ephemeral headwater tributaries can play a crucial role in driving main-stem sediment dynamics, even in temperate regions, and may be particularly important in catchments where main-stem rivers are regulated. Appreciation of this role is important, given climate change and related water scarcity, and the likely societal pressures for flow regulation to provide water for human needs.

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8. CONFLICT OF INTEREST

The authors declare no conflict of interest.

9. REFERENCE LIST

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FIGURES

Figure 1: Details of the study area and site: (A) Location of the study area within the UK. (B) The Ehen catchment, including the Ben Gill and upper Ehen sub-catchments. (C) A detailed map of the study area showing key features discussed in the text. The red dot shows location of the turbidity meter.

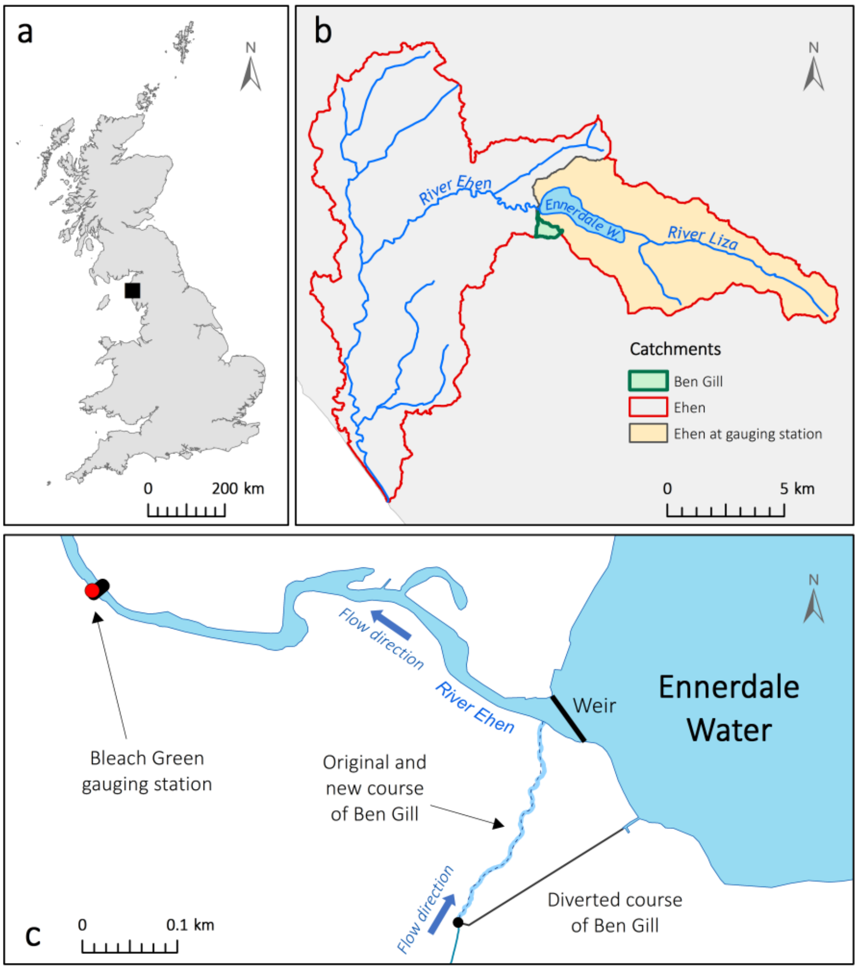


Figure 2: Calibration information for the turbidity probe, showing NTU-SSC relationships pre- (black dots) and post-reconnection (white dots) based on empirical calibration (see text for further details). Note that the starred value was found to have a high leverage on the pre-reconnection regression curve (Cook's distance > 1) and so was not used for the line fitting.

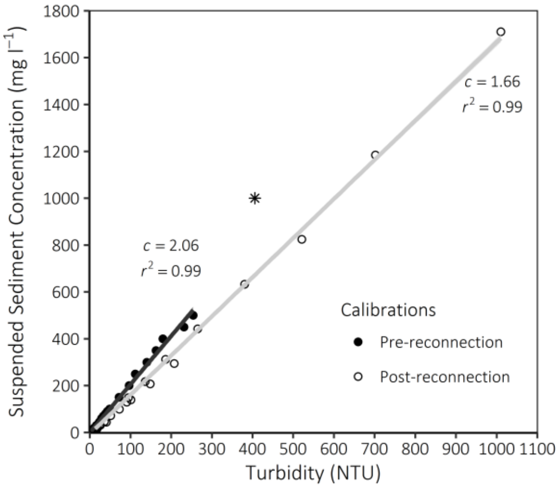


Figure 3: (A) Discharge of the River Ehen and local daily rainfall. (B) Suspended sediment concentration in the River Ehen. Discharge and suspended sediment concentration measured at Bleach Green at 15-min intervals. Rainfall was recorded at Ennerdale Bridge. Black arrow shows the day of Ben Gill reconnection.

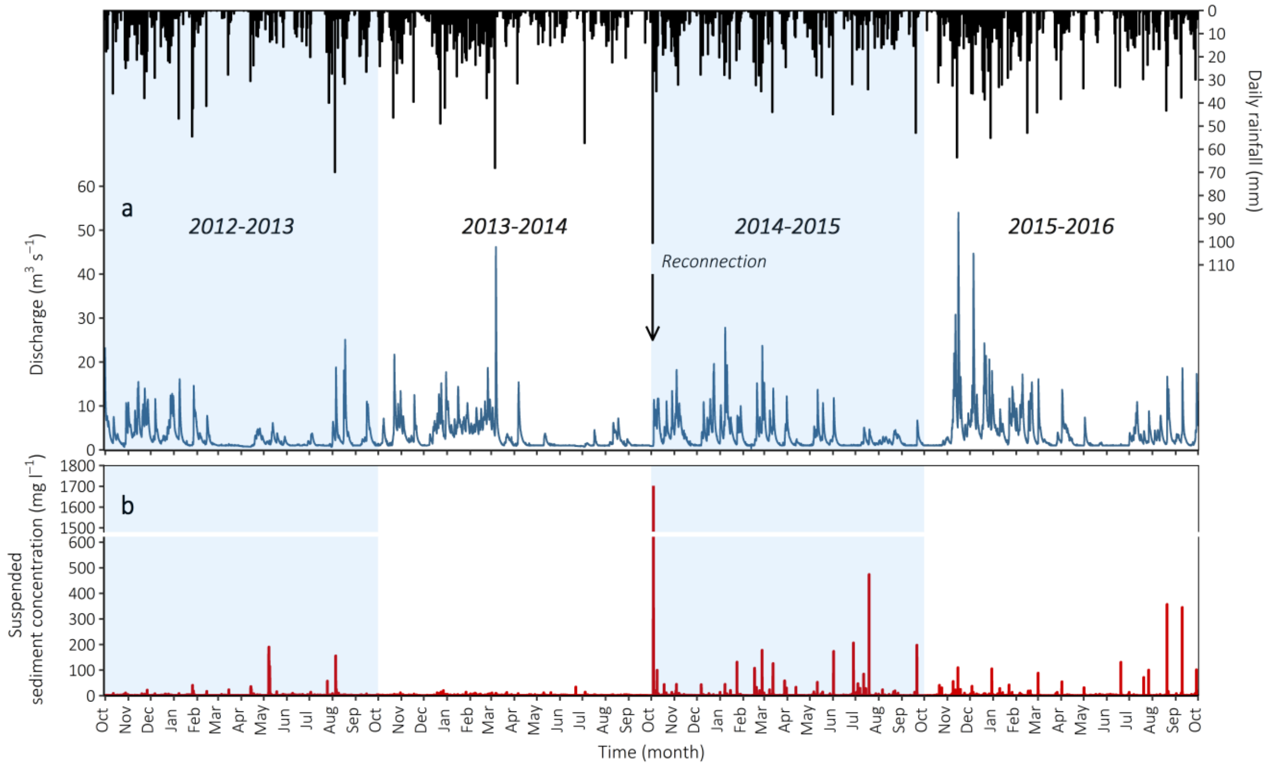


Figure 4: Flow duration curves of the study years expressed as the percentage of time a given discharge is equalled or exceeded. Data are for Bleach Green gauging station, measured at 15-min intervals. The inset table summarises key hydrological statistics for each year.

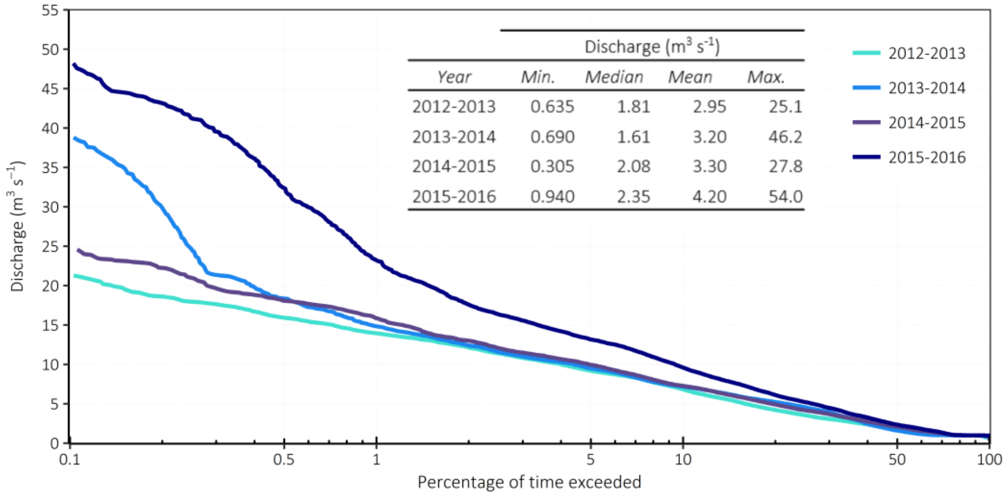


Figure 5: Relationship between discharge and suspended sediment concentration in the River Ehen, for the pre- reconnection (A) and post-reconnection (B) periods. Coloured rectangles in (B) highlight parts of the graph that are further described in the text. Data were recorded at Bleach Green at 15-min interval.

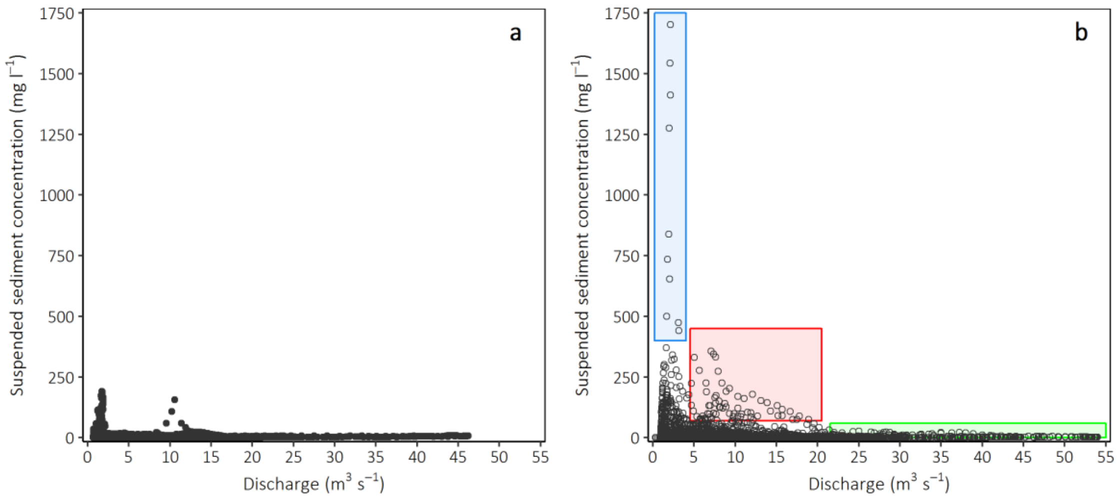


Figure 6: Monthly water and sediment yield for the study period.

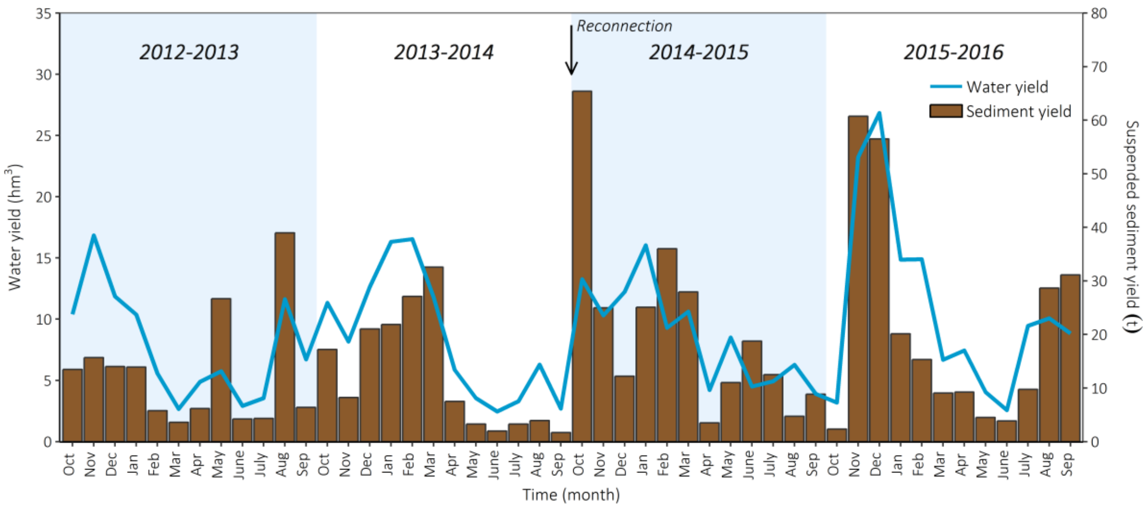


Figure 7: (A) Water and sediment yield for each of the hydrological years of the study period. (B) Change in water and suspended sediment yield following the reconnection. Changes are assessed in respective years relative to the pre-reconnection period.

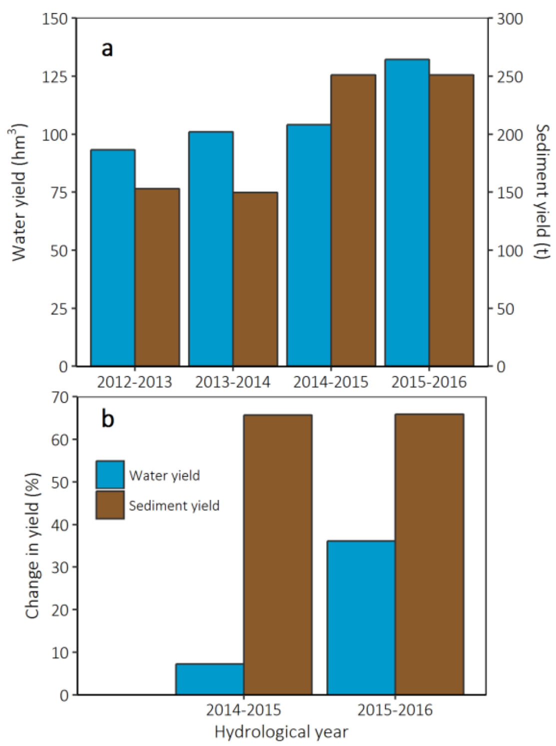
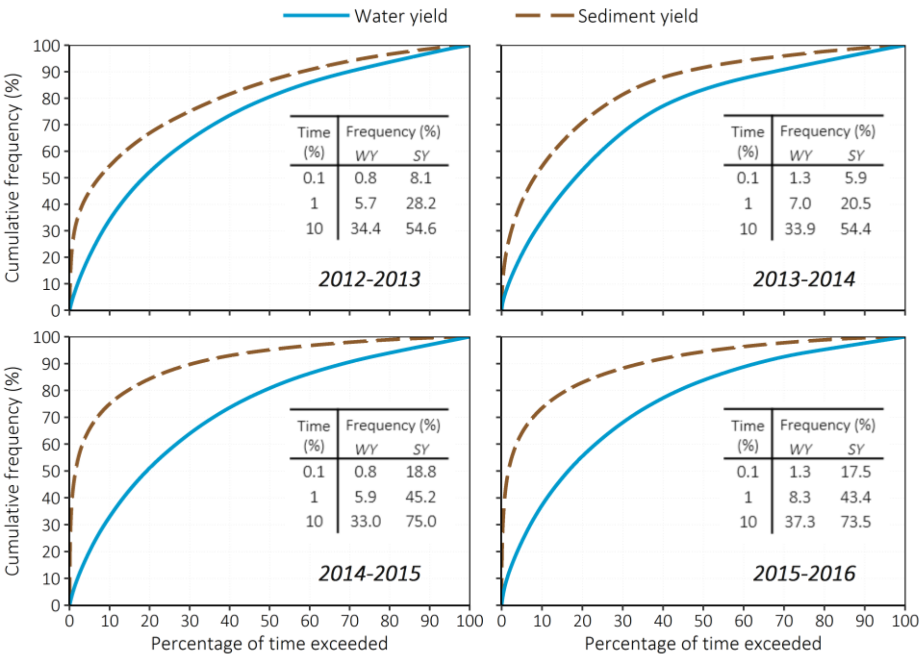


Figure 8: Cumulative frequency curves of water and suspended sediment yield for each of the hydrological years. Years 2012-2013 and 2013-2014 represent pre-reconnection data, while

years 2014-2015 and 2015-2016 represent post-reconnection data. Inset tables summarise some statistics for each of the years (i.e. key percentiles of water and sediment yield (WY and SY respectively) transported for a given proportion of time).



TABLES

Table 1: Statistics of suspended sediment concentration computed from 15-min data (Bleach Green gauging station) for the River Ehen. Note that 1st and 3rd Qt. indicate the first and the third quartile of the SSC data set.

	Suspended Sediment Concentration (mg l^{-1})					
Year	*Min.*	*1st Qt.*	*Median*	*Mean*	*3rd Qt.*	*Max.*
2012-2013	0.206	0.883	1.029	1.86	1.44	190
2013-2014	0.206	0.617	0.823	1.08	1.23	33.9
2014-2015	0.166	0.498	0.664	2.00	1.16	1702
2015-2016	0.166	0.498	0.664	1.37	1.00	357